Laser Experiments in Water and Sand

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LONG-TERM GOALS

The goal of this project is to develop technology to provide validation-quality data for calculations of shock and bubble interactions with a sand bottom. Tests conducted using a pulsed laser system in the Laboratory for Underwater Hydrodynamics (LUH) at the Naval Research Laboratory (NRL) will provide validation-quality data for studying shock propagation and cratering phenomena. The advantages of this approach are: (1) precisely controlled boundary conditions; (2) improved diagnostics; (3) extensive imaging capabilities to visualize the effect of the re-entrant jet and the cratering process; and (4) unique experiments including a simultaneously detonated line charge and stratified aerated sand conditions.

OBJECTIVES

The requirements for the set of experiments to be performed in FY00-FY01 are centered on the following technical objectives: (a) measure shock propagation and bubble expansion via pressure gauges and imaging in free-field water, in water on a rigid surface and in a stratifed aerated sand bottom, (b) collect data to determine the relative importance of shock and bubble energies in the cratering process, (c) collect data for 2D and 3D line charge phenomena, (d) develop an appropriate set of initial conditions for hydrocode simulations based on experimental data, and (e) incorporate the sand characterization into Navy hydrocode sand models such as the p-□ model.

APPROACH

Laboratory-scale tests designed to provide validation-quality data for numerical simulation codes such as DYSMAS/Gemini can be performed at NRL LUH laser facility. The laser can be focused to a small spot inside a water tank to produce kbar, cm-scale spherical shocks which are measured with pressure sensors, photography, shadowgraphy, and interferometry. For purposes of validating numerical simulation codes, a complete set of precise and comprehensive data of the relevant physical response phenomena is necessary. The data set must include time-resolved visual recording of the bubble interaction with the bottom during the expansion and collapse phases, including development and acceleration of the re-entrant jet, and crater development. To understand the cratering phenomena, the experiments must vary the intensity of the "explosion", i.e. energy, and quantify the energy partitioning between the bubble and shock. This energy partitioning may be accomplished by varying the laser energy, the focal spot size, and/or the size or type of the target.

In the shock propagation tests, the array of gauges must be capable of accurately measuring the very short-duration shock wave generated by the laser system. In addition to shocks from spherical charges, shock waves from line charges are of interest to the Navy. Since the LUH laser system can be focused as easily on a line as on a point, it is uniquely suited to develop data to explore two and three dimensional line charge phenomena to validate compressible hydrocode computations. The key is that if the laser beam is focused into a line, and the target is a line, we can achieve the effect of detonating a line charge simultaneously along its entire length, something that is impossible to do, as a practical matter, with explosives. The LUH experiments are being conducted by Jacob Grun and Theodore Jones, NRL Code 6795, and Charles Manka, Research Support Instruments, Inc.

Given that the condition of a sand bottom can be adequately controlled and measured, the LUH facility is being used to assess the effect of stratified aerated sand on performance of explosives on the surface. In both the cratering and shock tests, it is necessary that the sand-water-air mixture that makes up the bottom be well characterized with respect to density, air content, compression properties and flow properties. The sand characterization work is being conducted by L. Dale Bibee, NRL Code 7432.

The modeling of the experiments can be accomplished using the DYSMAS/Gemini code for shock propagation, bubble dynamics and cratering. Since the shock and the bubble are generated with a laser and not explosives, the deposition of laser energy to form the shock and bubble must be converted into a form compatible with hydrocode initial conditions so that the numerical modeling can be started. These simulations are being performed by Alexandra Landsberg and Daniel Tam at NSWC Indian Head Division (NSWC-IHD), Code 420.

WORK COMPLETED

LUH Experiments. In FY00, the LUH chamber was outfitted with diagnostics, including dark-field imaging, bright-field imaging, fiber-optic pressure gauges, a sand-core sampler, and a 3D air content tomography diagnostic. Over 50 shock and bubble experiments were performed in both free-field water and near a rigid surface. The sensitivity of the bubbles to variations of experimental parameters such as laser focal spot size, laser energy, target material and source aspect ratio was examined. Bubble-sand bottom interaction experiments were designed and started in September 2000 and will continue in FY01. The design of a simultaneously detonated line charge experiment using a line-focused laser beam was also completed and will be performed in FY01. In addition, development of imaging diagnostics for sand bottom cratering is complete.

Sand Aeration. Sand aeration levels of 0.3 to 2% as measured with the core sampler were produced as well as stratified sand conditions which varied from 0% to 1% over 20cm. Using 3D tomographic diagnostics, the sand aeration conditions were characterized.

Theory and Simulations. The DYSMAS/Gemini simulations were initialized as a function of energy and volume while the LUH experiments were a function of laser energy, spot size and target material (to a lesser extent). In FY00, a series of 1D spherical DYSMAS/Gemini simulations was performed to compare to LUH shock pressure traces. A series of 2D axisymmetric sensitivity studies was performed to understand the effect of the initial conditions on shock pressure and bubble dynamics. These simulations were compared to bubble theory and LUH bubble data.

RESULTS

LUH Experiments. A new fiber optic pressure gauge was fielded by upgrading the manufacturer's electronics with much faster readout electronics developed by NRL. With these gauges 50ns rise-times were recorded in the LUH. The signal produced by the gauges is free of electrical noise. Dark-field and bright field imaging utilizes a Cordin 377 camera. The Cordin Model 377 is a high speed rotating-drum framing camera which can record at any speed between 1,000 and 200,000 frames per second with a shutter time between 1.63 to 328 μ sec. Better sequential images of the bubble expansion and collapse were produced using a new high-intensity magnesium flashbulb backlighter. Using this optical system the LUH is able to visualize the interior of bubbles including re-entrant jets.

Typical results from the free-field bubble experiments are shown in Figure 1. The results of these experiments were transmitted to NSWC/IHD where the appropriate initial conditions for the DYSMAS/GEMINI code were determined. The sensitivity of the code to changes in these conditions were determined and the code results were compared to experimental measurements. These shots were also used to activate the fiber optic pressure sensors and to optimize the performance of dark-field shadowgraphy, with particular emphasis on its being able to visualize the internal structure in a bubble. In these experiments the laser energy and the distance between the point of laser focus and the target was varied. In addition several shots examined the interaction of a bubble with a nearby surface.

Figure 1. Bubble expansion and collapse sequence in shot 074. The interframe time is 114 microseconds and the laser energy @ 532 nm is 169 Joules. The field of view is 7.6 x 10.3 cm.

Sand Aeration. The critical sand property related to shock propagation efficiency is expected to be the amount of air trapped in the pore space between grains. For shocks generated in water near a sand-water interface, the energy is rapidly attenuated with distance for highly aerated sand because aerated sand is highly compressible and acts as a pressure relief surface at the interface. This is precisely the geometry for mine clearance charges deployed against a bottom mine. Aeration levels in typical surf zone sands are on the order of 0.5%, but values as high as 4-5% have been measured in some cases. Generation and characterization of aeration levels in these ranges are the objectives of the Laboratory for Underwater Hydrodynamic shock tests at NRL.

ASTM C778 standard Ottawa sand was placed in the removable, porous-bottom LUH chamber sand tray through which aerated and de-aerated water was pumped. The chamber was left at atmospheric pressure while water was pumped through the sand. With this procedure, aeration levels of 0.3 to 2% were achieved as measured with the core sampler. The LUH also successfully produced a 20 cm deep stratified water-air-sand mixture in which the amount of air at 2 cm beneath the surface was 0% and approximately 1% at a depth of 17cm. An example of the measurement of the stratified mixture, performed with the 3D geo-acoustic imaging diagnostic, is shown in Figure 2.

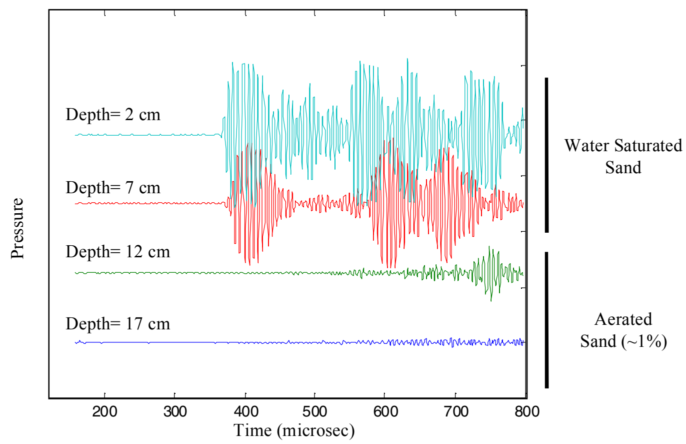

Figure 2. Sound transmission through sand at various depths beneath the surface of stratified aerated sand-air-water mixture. The vertical scale is the sound pressure in arbitrary units.

Theory and Simulations. The goal of the numerical simulations is to: (a) understand how initial conditions in the code correspond to experimental initial conditions and (b) understand how initial conditions affect shock pressure and bubble dynamics. The simulations are a function of initial energy and volume while the LUH experiments were a function of laser energy, spot size and target material (to a much lesser extent). In FY00, 1D DYSMAS/Gemini simulations were shown to agree with an LUH pressure trace for a free-field shock. A series of 2D sensitivity studies showed that (a) high aspect ratio targets produce non-spherical pressure distributions, (b) varying the initial energy affects both the shock pressure and maximum bubble radius, and (c) varying the initial volume increases the shock pressure but has a smaller effect on bubble dynamics.

There is extensive theoretical and experimental analysis of the behavior of explosion bubbles. A series of simulations were performed which demonstrated that the error in maximum bubble radius is less than 2% compared to theory. The LUH provided data on the bubble dynamics based on the bubble imaging as shown in Figure 1. Figure 3 (left) shows two shots for the same laser energy and spot size with two different target materials. The shot shown with blue triangles used a 2 mil thick brass, while the shot shown with red triangles used 3 mil thick Kapton plastic. The results show that target material does not have much effect on bubble dynamics in the first period. The simulation agrees with the experimental data provided by the LUH. Using the energy from another laser shot, the ratio of laser energies was used to determine the initial conditions for the simulation. In Figure 3 (right), the red and blue triangles are experimental data for two different laser energies while the black lines are the corresponding simulation results. In terms of bubble dynamics, the laser experiments match closely with simulations. Additional experimental and simulation results were compared, with the difference between the two generally being less than 5%. Given experimental pressure traces and bubble dynamics, an appropriate set of initial conditions for numerical simulations can be determined.

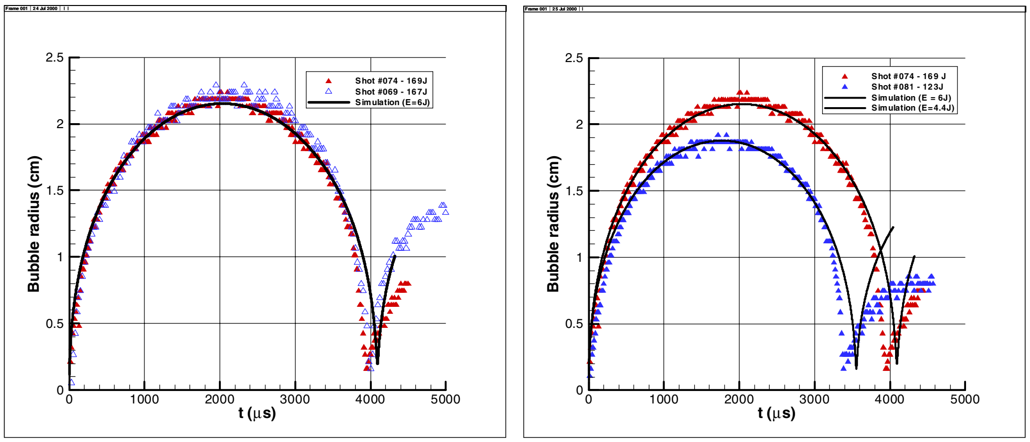

Figure 3. Comparison of bubble dynamics from experiment and simulation. The left figure shows two laser shots at the same energy and spot size with different target materials. The right figure shows two laser energies with the same spot size and target material.

IMPACT/APPLICATION

The direct impact is in providing validation-quality data for Navy hydrocode calculations of shock and bubble interactions with a sand bottom. The hydrocode simulations are an invaluable tool for helping understand mine countermeasures systems. The pressure sensor technology developed in the LUH and the improvements in sediment characterization techniques are directly applicable to field experiments. These experiments also help in understanding air transport and stability in sediments.

TRANSITIONS

The results of this task will be used to improve the Navy's ability to model the effect of explosives in or near the sea bottom. Related projects (see below) are building upon these experimental and computational results for mine countermeasures and torpedo warhead design.

RELATED PROJECTS

The LUH is also studying bubble-plate interactions under the ONR Underwater Weapons program. A collaborative effort by the NRL LUH, NSWC-IHD, and Advanced Technology and Research Corp is studying an advanced torpedo warhead concept using directed energy experiments under the ONR Underwater Weapons program. Based on results of the current task, a new research project is being funded by NRL to understand the non-linear effects of laser propagation and focusing in water.

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